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Technical Report

GRAVITY VENTILATION OF UNDERGROUND SHELTERS

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GRAVITY VENTILATION OF UNDERGROUND SHELTERS

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by

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ABSTRACT

Tests were conducted to determine the suitability of using gravity ventilation as an emergency method of providing air for survival in an underground shelter. The tests consisted of inducing through a simulated test shelter an airflow caused by (a) inside-outside temperature differentials, and (b) stack heaters in the exhaust duct. An additional test was made which involved a device to direct wind into the intake duct. It was found that wind blowing over the inlet and exhaust ducts created a negative pressure in the shelter that could not be satisfactorily overcome by the gravity methods used; thus, minimum ventilation rates could be obtained only when there was no wind blowing.

In the tests conducted to utilize the wind, an NCEL-designed air inducer which mounts on the inlet duct provided satisfactory ventilation during normal weather conditions when there was a wind of 6 to 8 mph.

INTRODUCTION

A critical problem in assuring the survival of inhabitants of underground shelters is providing an adequate ventilation system. The usual criteria on shelter ventilation systems require power-operated blowers. However, there is a requirement for minimum ventilation that could supply sufficient air when mechanical systems fail.

NCEL was assigned the task of investigating an emergency ventilation system that would utilize the effect of gravity on the density differential between shelter air and outside air to induce natural convection air currents to flow. Included in the investigation were means of augmenting the natural density difference by (a) an exhaust-stack heater and (b) utilizing wind forces. The task objectives were pursued by determining the airflow in an above-ground test shelter with various density differences and methods of wind utilization. This report includes results of these tests, which indicate that gravity ventilation alone does not provide satisfactory shelter ventilation. However, wind power can provide satisfactory ventilation during average wind conditions.

GRAVITY VENTILATION TESTS

Procedures. There is a motive head, or draft, produced by the difference in weight between a column of heated air and a similar column of unheated air. In an underground shelter, the air is heated by rejection of body heat from the occupants. The column of heated (and less dense) air will rise, thus creating convective air currents. The draft available is expressed by the formula,

$$h_a = H_T(\rho_o - \rho_i) \tag{1}$$

where h_a = available draft head (feet of air)

H_T = vertical distance of the heated column of air (feet)

ρ_o = density of outside air (lb/ft^3)

ρ_i = density of inside air (lb/ft^3)

To determine the amount of ventilation that would occur from various combinations of inside-outside temperature differentials (Δt) and vertical heights of a heated column of air, a test setup was constructed which consisted of a shelter with inlet and exhaust ducts and with electrical heaters to control the shelter air temperature. A schematic of the test setup is shown in Figure 1.

The shelter, which had a cross section of 8 x 8 feet and a length of 12 feet, was erected on the inside of a 22 x 50-foot Quonset building at NCEL. The shelter was constructed of 3/4-inch-thick plywood, all of the joints were sealed airtight, and the outside was covered with 1-inch-thick fiberglass insulation.

Inlet and exhaust ducts made of galvanized sheet metal were connected into the shelter. Each duct extended through a hole in the roof of the Quonset building to the outside air. The height of the inlet duct was fixed at 13 feet, and the centerline of the opening into the shelter was 1 foot above the shelter floor. The exhaust stack was connected to the top of the shelter, and lengths of 8, 12, and 16 feet were used. These lengths provided effective stack heights of 15, 19, and 23 feet, counting 7 feet inside the shelter. Two intake-and-exhaust duct systems were used; one was 8 inches in diameter, and the other was 12 inches in diameter. An enclosure which could hold a 2-inch-thick, 18-inch-square dust filter was installed on the inlet side. Tests were normally conducted without the filter; however, a limited number of tests were made with it.

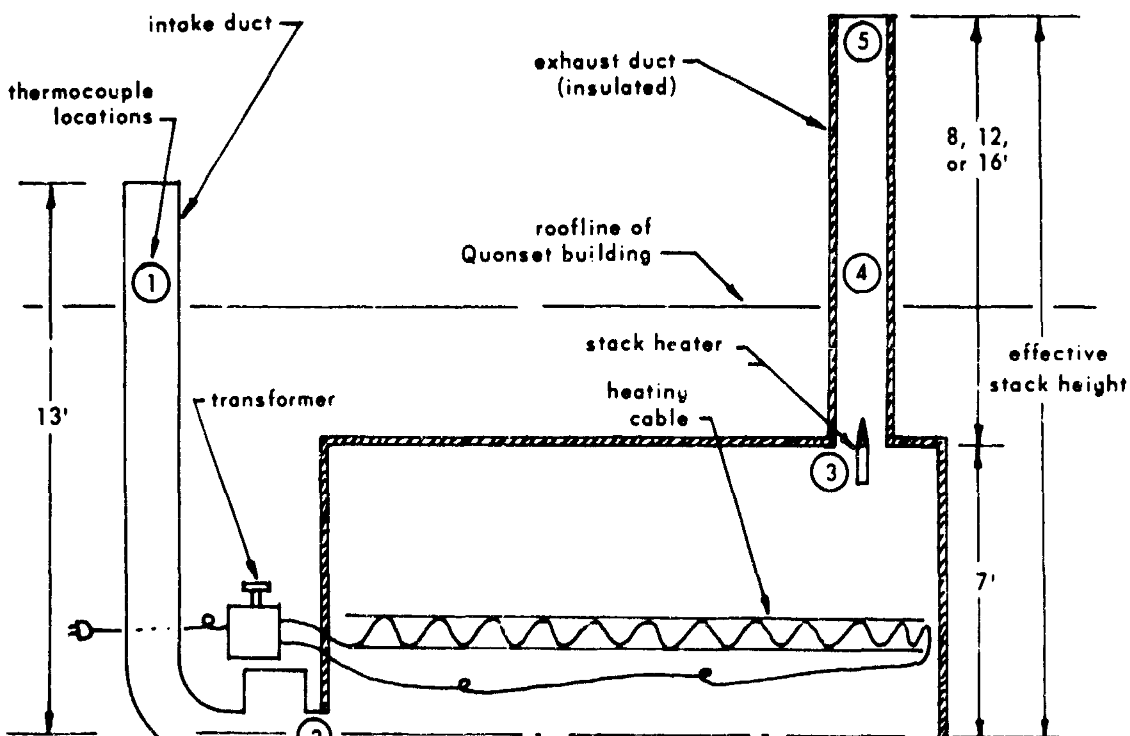

Figure 1. Test setup for investigating ventilation of underground shelters (not to scale).

Thermocouples were installed to measure inside and outside air temperatures. The outside temperature was indicated by thermocouples 1 and 2 (see Figure 1). The inside temperature was indicated by thermocouples 3, 4, and 5. The Δt is the difference in average readings between the outside temperature and the inside temperature. For the tests, Δt's of 10°F and 20°F were used with each of the three exhaust-stack heights. The shelter air was heated by 960 feet of electric heating cable that was spaced to distribute the heat evenly. A transformer connected in series with the cable permitted control of the cable heat output. An inside view of the shelter is given in Figure 2, and an exterior view of the intake side is shown in Figure 3.

Velocity of the air drawn into the shelter was measured by a hot-wire anemometer, the probe of which was in the inlet duct. Airflow patterns were observed by injecting colored chalk dust into the duct. Outside wind velocities were measured by a 3-cup totalizing anemometer that was mounted on the roof of the Quonset building.

Results. The first tests were conducted during normal weather conditions when the average wind velocity at the test site varied from 5 to 8 mph. Under these conditions, air in the ducts was in a state of turbulence, and any net airflow that might have passed through the shelter could not be detected. The anemometer could not be used in such turbulent air, and dust particles injected into the vertical section of the inlet duct traveled up as well as down. This situation existed even when the largest draft-producing condition of a 20°F Δt and a 16-foot exhaust duct was used.

A number of experiments were conducted in which the inlet duct was protected from the wind so that the opening was in still air. Under these conditions, smooth flow was obtained.

Because of the wind problem, it was necessary to conduct tests during dead calm weather. Results of these tests are in Table I. The data shows that the largest ventilation rate (160 cfm) was obtained with a Δt of 20°F and the 12-inch-diameter duct system with the 16-foot exhaust stack. Conversely, the lowest flow (61 cfm) was obtained with a Δt of 10°F and the 8-inch-diameter duct system with a 8-foot exhaust stack.

During conditions when the stack height and Δt of each duct system were the same, the ventilation rate with 12-inch-diameter ducts was usually about twice the rate with 8-inch-diameter ducts, although the velocity was always higher in the 8-inch ducts. This indicates that a considerable portion of the available draft in the 8-inch ducts is expended in imparting kinetic energy to the ventilation air. The data also show that the ventilation rate obtained with 20°F Δt was only slightly greater than the rate with a 10°F Δt. Several tests with the filter installed showed that the filter would reduce the velocity by about 10%.

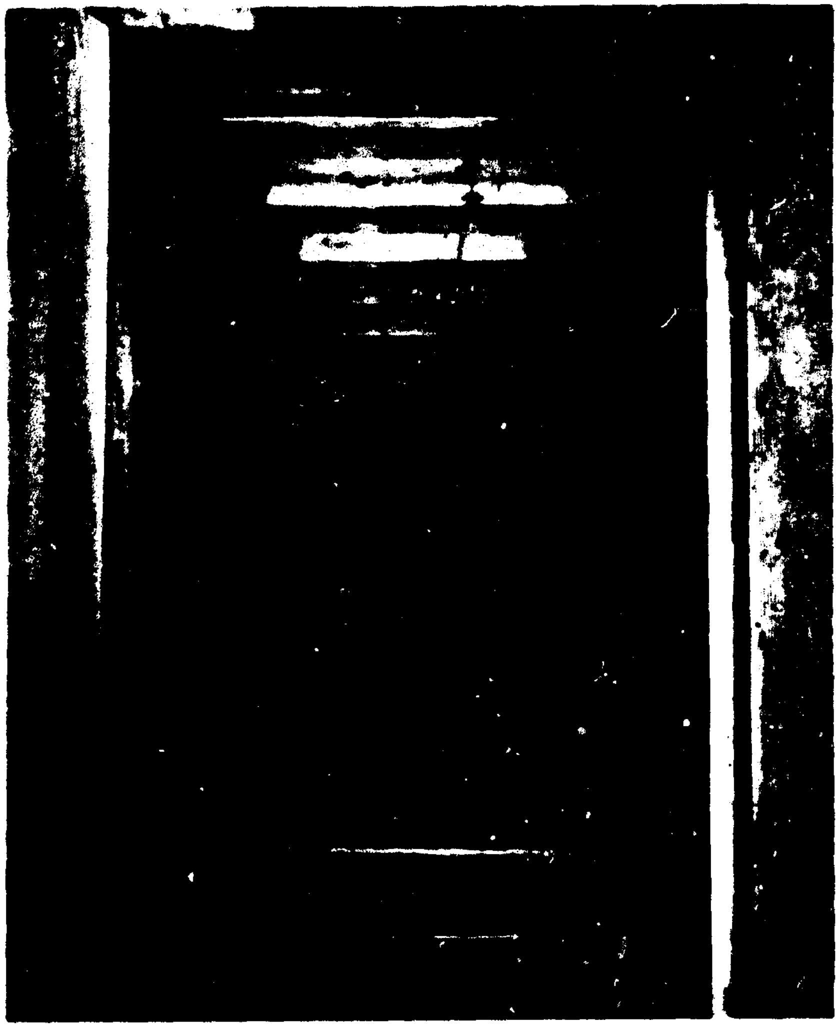

Figure 2. Interior of test shelter. Heating cables can be seen, as well as intake-duct opening.

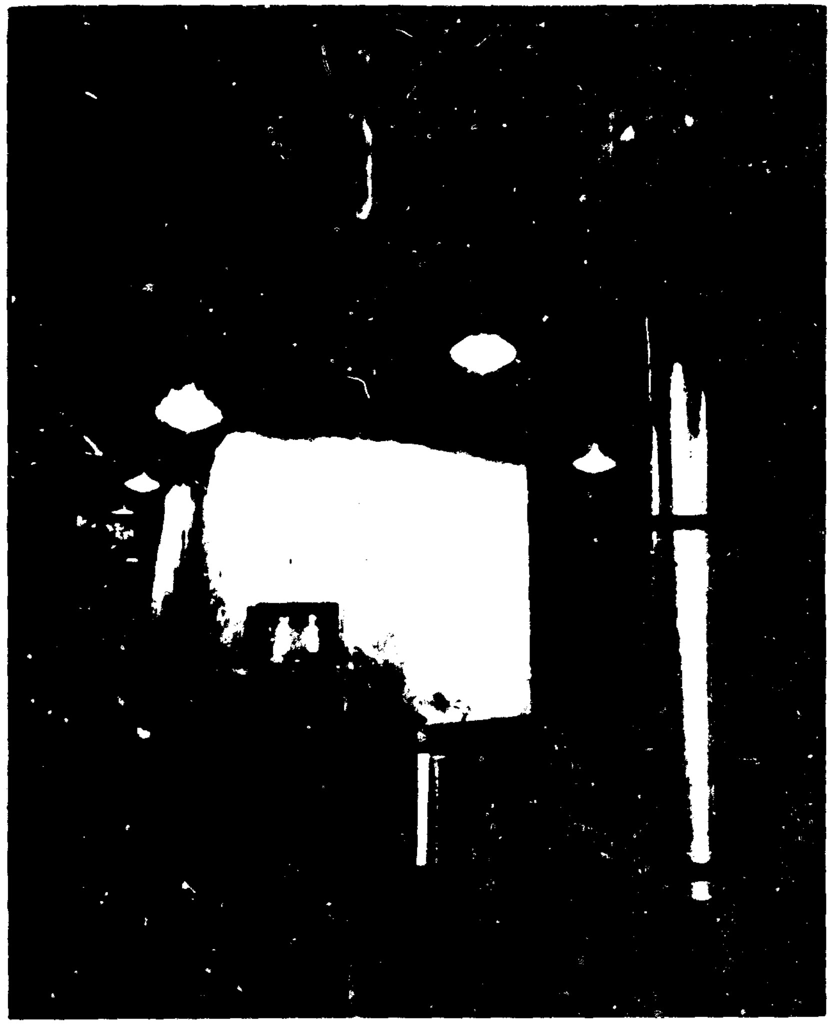

Figure 3. Test shelter and inlet duct in the Quonset building.

Table I. Air Velocities and Calculated Ventilation Rates From Gravity Ventilation Tests

Exhaust Stack Height 1/ (ft)	8-Inch Ducts						12-Inch Ducts			
	10°F Δt			20°F Δt			10°F Δt		20°F Δt	
	V	Q	V_F	V	Q	V_F	V	Q	V	Q
8	120	42	—	175	61	150	79	101	87	111
12	170	60	155	200	70	—	96	122	105	134
16	190	66	—	220	77	190	122	155	125	160

1/ For effective stack height, add 7 feet.

Notation: V = Air velocity (fpm) without a filter

V_F = Air velocity (fpm) with a 2-inch thick, 18-inch-square dust filter

Q = Calculated ventilation rate (cfm)

VENTILATION TESTS WITH STACK HEATERS

Purpose. Figure 4, which is taken from the ASHRAE Guide,* shows that there is a decrease in sensible heat rejection as the ambient air temperature increases. Thus, temperature differences caused by heat rejection of shelter occupants are unreliable sources of energy. This problem is compounded by the fact that increased ventilation is needed at the higher temperatures to keep the effective temperature at a habitable level. Seasonal as well as daily weather conditions also influence the temperature differences. For example, in the case of underground shelters, on a warm day in the spring or early summer, cold ground temperatures and warm outside-air temperatures could result in little or no temperature differences. To assist in the flow of air during unfavorable conditions, an exhaust stack heater could be utilized to induce ventilation. Under these conditions, total draft is expressed by the equation,

$$h_a = H_1(\rho_o - \rho_i) + H_2(\rho_o - \rho_s) \tag{2}$$

where h_a = available draft head (feet of air)

H_1 = vertical distance from centerline of inlet duct to top of shelter (feet)

H_2 = vertical distance from top of shelter to top of exhaust stack (feet)

ρ_s = density of exhaust-stack air (lb/ft^3)

Procedure. The effectiveness of using a stack heater for ventilation was investigated by utilizing the shelter, duct system, electric heating cable, and instrumentation of the gravity ventilation tests previously described. The stack heater was placed at the lower end of the exhaust duct as shown in Figure 1. It consisted of propane torch tips in which outputs of 4,800, 9,600, and 54,000 Btu per hour could be obtained. Fuel was supplied by a 25-gallon propane tank located outside the Quonset building.

Airflow measurements were made using each heat output with each of the three exhaust-stack heights. Tests were conducted with Δt's of 0, 10, and 20°F, using first the 8-inch diameter and then the 12-inch-diameter duct system.

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*ASHRAE Guide and Data Book, 1961: Fundamentals and Equipment. American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc. New York, N. Y.

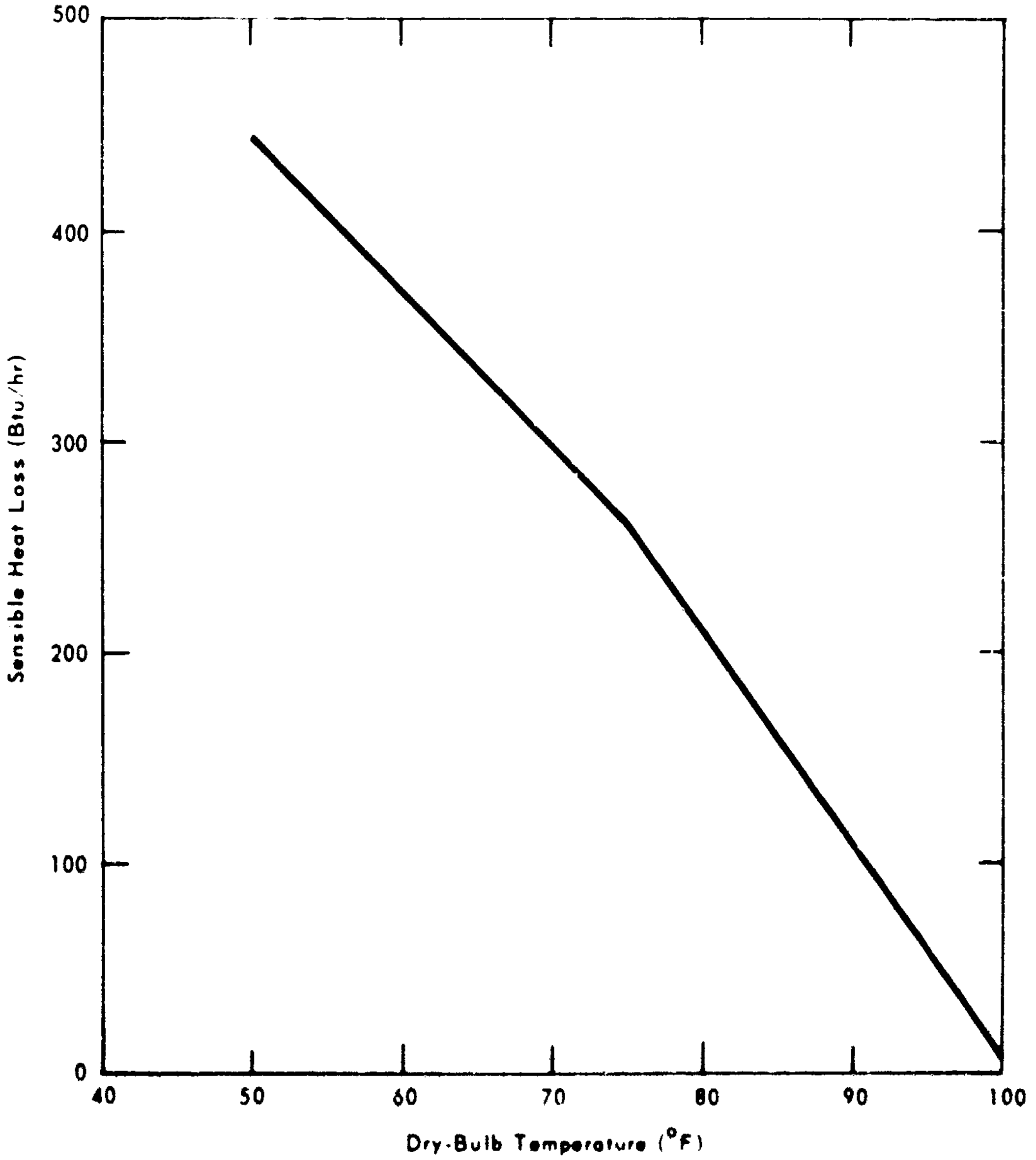

Figure 4. Sensible heat loss by radiation and convection versus dry-bulb temperature for average man at rest.

Results. Tests which were conducted during normal weather conditions again showed that the drafts produced by gravity ventilation, even with stack heaters, could not satisfactorily overcome the opposing negative pressure created in the inlet duct by the wind. When the 54,000 Btu per hour burner was used, some net gain could be detected by observing dust particles, but turbulence was still too great to permit accurate measurements. Figure 5 is a recording of air velocities when using the 12-foot exhaust stack of the 12-inch-diameter duct system at a Δt of $0^{\circ}F$. The left side of the figure shows the airflow when both ducts were exposed to an 8-mph wind. The right side of the figure shows how the flow became reasonably smooth when the inlet-duct opening was protected from the wind.

A series of tests was then conducted in dead calm weather using all combinations of stack heights and stack heater sizes with shelter Δt's of 0, 10, and $20^{\circ}F$. The results are in Table II.

The data show that the largest ventilation rate obtained was 311 cfm. This occurred with the 12-inch-diameter duct system used in combination with the largest draft conditions consisting of the 54,000 Btu per hour stack heater, a $20^{\circ}F$ Δt, and the 16-foot exhaust stack. The smallest rate of 53 cfm occurred in the 8-inch-diameter duct system with the lowest draft produced by the 4,800 Btu per hour heater with the 8-foot exhaust stack.

The pattern of results is similar to those in Table I in that the ventilation rate with 12-inch-diameter ducts was usually about twice the rate obtained with 8-inch-diameter ducts, although the flow velocity in the latter was considerably greater.

It is again shown that only small increases in cfm were obtained when the Δt was increased from $10^{\circ}F$ to $20^{\circ}F$. It may also be noted that significant gains in ventilation were not obtained when combined heads of a Δt and a stack heater were used. As an illustration, the 9,600 Btu per hour burner with $0^{\circ}F$ Δt caused 153 cfm to flow in the 12-inch-diameter ducts with the 16-foot exhaust stack. Similar conditions without the burner, but with $10^{\circ}F$ Δt, resulted in 155 cfm. With both the $10^{\circ}F$ Δt and the 9,600 Btu per hour burner, the ventilation was increased only to 189 cfm.

Comparison of data for the various stack heaters shows that the small heaters were utilized more efficiently than the large one. The filter test data are similar to the data of Table I, in that the filter reduced the flow velocity by about 10%.

WIND POWER VENTILATION TESTS

Purpose. The Los Angeles Weather Bureau records show that the city has calm weather, i.e., wind velocity of 0 to 1 mph, less than 1% of the time, and that calm periods usually last 1/2 hour or less and occasionally for an hour. The ASHRAE Guide gives the average wind velocities of 200 cities in the United States. These wind velocities average 9.5 mph, with only 4 cities having average velocities less than 5 mph. The percentage of time that these velocities occurred is not given, but it appears that all cities listed have enough wind to reduce the flow of air induced through a shelter by gravity ventilation. Therefore, experiments were directed toward utilizing the wind for ventilation.

An equation for calculating the quantity of air forced through ventilation openings by the wind is given in the ASHRAE Guide as

$$Q = EAV \tag{3}$$

where Q = airflow (cfm)

A = free area of inlet opening (ft^2)

V = wind velocity (fpm)

E = effectiveness of opening (0.60 for perpendicular winds)

If a 5-mph wind, which is one of the lower recorded average velocities in the ASHRAE Guide, were directed into the 12-inch-diameter duct of the test shelter, calculations indicate a ventilation rate of 207 cfm. This rate might be increased by the drafts produced by temperature difference and by the negative pressure on the exhaust duct. Considering the fact that most places have average wind velocities higher than 5 mph, utilization of wind appeared to be a promising method of providing emergency ventilation.

Procedure. The test shelter with the 12-inch-diameter duct system and the 12-foot exhaust stack was used to investigate various methods of using wind power for ventilation. The methods were tested by observing dust patterns and by taking recordings of wind velocities at the same time that recordings were taken of air velocities in the inlet duct.

Methods and Results. The first method investigated was a 90-degree elbow mounted on the inlet duct with the opening directed into the wind. A smooth airflow in the duct was obtained; however, large decreases in flow would occur with a small change of wind direction. An attempt was made to increase the flow by mounting another elbow on the exhaust duct with the opening directed away from the wind; however, no increase could be detected.

Another method utilized a Breidert exhauster on the exhaust duct, and nothing on the intake duct. This method was unsatisfactory because the exhauster could not satisfactorily operate against the negative pressure in the shelter created by wind at the intake duct.

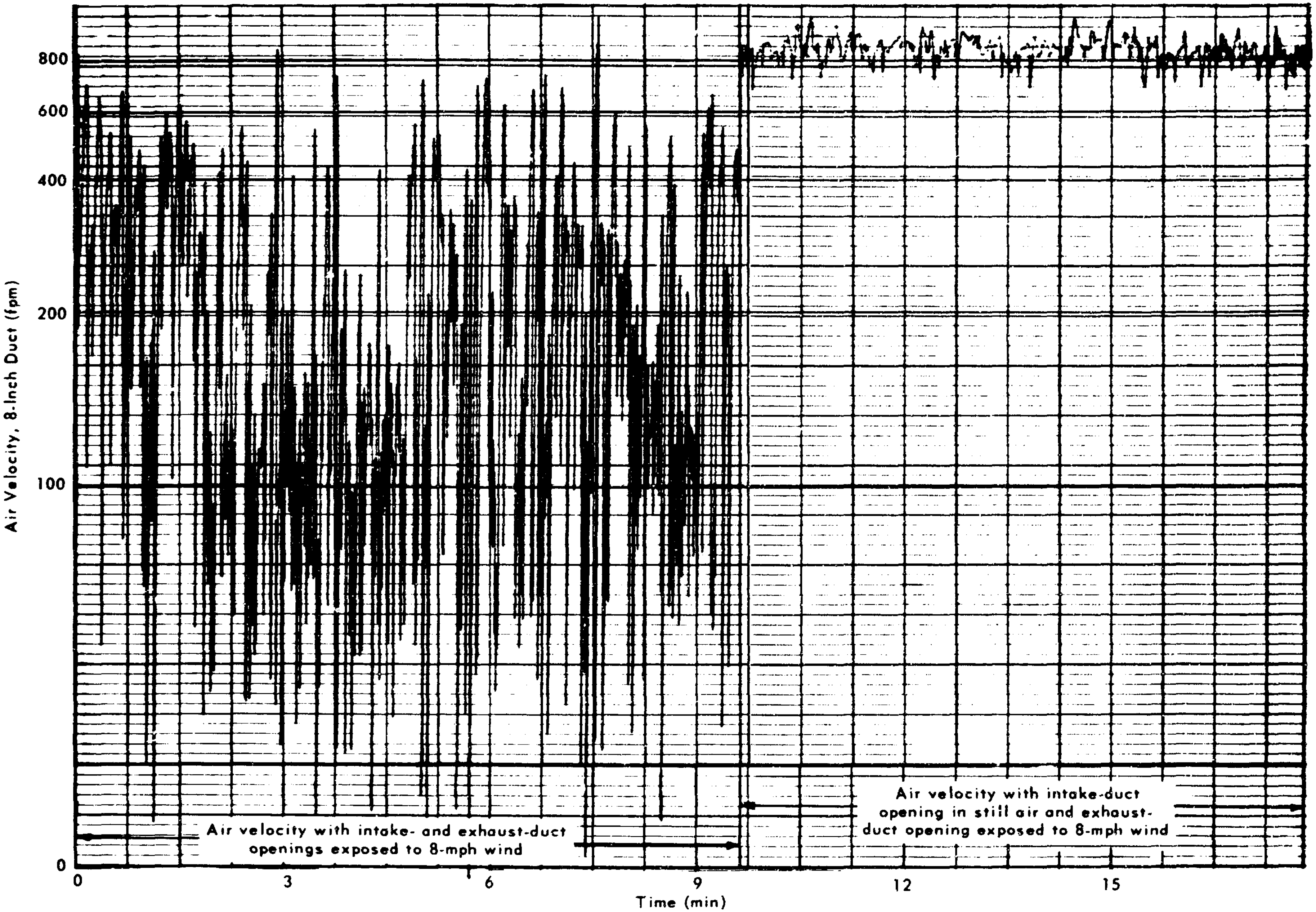

Figure 5. Air-velocity recordings taken during tests of the gravity ventilation system. Recordings were made with a 54,000 Btu per hour burner in a 12-foot exhaust stack and a Δt of 20°F.

Table II. Air Velocities and Calculated Ventilation Rates From Gravity Ventilation Tests With Stack Heaters

Burner Size (Btu/hour)	Exhaust Stack Height[1/] (ft)	8-Inch Ducts									12-Inch Ducts					
		0°F Δt			10°F Δt			20°F Δt			0°F Δt		10°F Δt		20°F Δt	
		V	Q	V_F	V	Q	V_F	V	Q	V_F	V	Q	V	Q	V	Q
4,800	8	150	53	—	200	70	—	240	84	220	61	78	113	144	122	155
	12	180	63	—	220	77	200	290	101	—	87	111	140	178	148	189
	16	185	65	175	275	96	—	325	113	—	105	134	148	189	155	197
9,600	8	175	61	—	210	73	—	225	79	220	70	89	122	155	131	169
	12	190	66	—	220	77	210	300	105	—	87	110	140	178	157	200
	16	220	77	205	325	113	—	375	131	—	120	153	148	189	165	210
54,000	8	220	77	—	350	122	—	400	140	370	140	178	157	200	157	200
	12	260	90	—	420	147	390	500	175	—	175	222	210	268	226	288
	16	310	108	290	475	166	—	550	192	—	210	268	236	301	244	311

1/ For effective stack height, add 7 feet.

Notation: V = Air velocity (fpm) without a filter

V_F = Air velocity (fpm) with a 2-inch thick, 18-inch square dust filter

Q = Calculated ventilation rate (cfm)

The next method utilized an NCEL air inducer on the intake duct. The inducer, which is described in the Appendix, will direct wind from any direction into the intake duct. A smooth airflow was obtained, and 5-minute recordings of wind velocity versus airflow were taken. Results were averaged and are displayed in Table III. Since results were encouraging, additional tests were conducted in which the inducer was used with the 8-inch-diameter duct system. Results are also in Table III. The 249 cfm obtained with the 12-inch duct system was about twice the rate obtained with the 8-inch ducts, although the air velocity in the 8-inch-diameter system was greater.

Table III. Average Air Velocity and Calculated Ventilation Rate With Air Inducer on Inlet Duct

(wind velocity from 5 to 8 mph)

Duct Diameter (in.)	Air Velocity (fpm)	Ventilation Rate (cfm)
8	350	122
12	317	249

The filter was put into the system during tests with the 8-inch system, but no decrease in flow could be detected. Also, a Δt of 20°F was applied, but no increase in flow could be detected. If the tests had been conducted in a wind tunnel with constant wind velocities, some increase probably could have been noted when the shelter was heated, and some decrease probably would have occurred when the filter was installed; however, the changes were too minor to be detected by the measuring methods used.

SUMMARY OF RESULTS

1. Ventilation by gravity flow provides a minimum ventilation rate only when there is an inside-outside temperature differential of about 10°F or more and when there is no wind blowing.

2. Ventilation with stack heaters provides a minimum ventilation rate when there is no inside-outside temperature differential and no wind blowing.

3. An air inducer mounted on the intake duct results in a sizeable improvement in ventilation rates over gravity flow both with and without stack heaters.

CONCLUSIONS

1. Ventilation by gravity flow is not suited for underground shelters because (a) there are many occasions when there will be no temperature difference to induce a flow of air; (b) there are many occasions when hot weather will require large amounts of air to maintain a habitable shelter environment; and (c) it will not operate against a negative pressure caused by wind at the inlet duct.

2. Gravity ventilation utilizing stack heaters is not suitable for underground shelters because (a) there are many occasions when hot weather will require large amounts of air to maintain a habitable shelter environment; and (b) it will not operate against a negative pressure caused by wind at the inlet duct.

3. Ventilation by use of the air inducer is suitable for underground shelters, because wind is nearly always blowing.

RECOMMENDATIONS

1. Wind power ventilation methods should be considered for use with underground shelters.

2. The NCEL inducer should be further developed to effectively utilize wind power.

ACKNOWLEDGMENT

Mr. Earl J. Beck of NCEL initiated the concept of using gravity ventilation for protective shelters, and he offered advice concerning the theory of gravity airflow.

Appendix

DESCRIPTION OF NCEL AIR INDUCER

The NCEL air inducer is designed to take advantage of winds to provide shelter ventilation. It functions by diverting wind from any direction into the shelter. Simultaneously, wind that blows over the outside opening of the exhaust duct creates a low-pressure area which draws air out of the shelter. A diagram showing use of wind in this manner is in Figure 6.

Figure 7 is a drawing of the air inducer, and Figure 8 is a photograph. With reference to Figure 7, the top of the inducer is 24 inches in diameter, the transition section (1) tapers at a 30-degree angle, and the bottom opening fits a 12-inch-diameter duct. The device has 5 vanes (2) that join at equal angles in the center and extend to the outer edge of the device. The inside upper edge is cut in the shape of a quarter circle, and a curved deflector (3) is welded to this edge. Wind that strikes the device from any direction will be diverted into the device by either 2 or 3 of the vanes, and the curved deflector will simultaneously divert the wind downward and into a shelter. The vanes are extended into the throat of the device to prevent the air stream from turning below the vanes and being exhausted on the leeward side.

The inducer was constructed of sheet metal; thus, it is suitable only for a fallout shelter. It could, however, be constructed of heavy gage steel which would make it suitable for blast-resistant shelters.

The air inducer was designed primarily for shelter use; however, it could be used to ventilate any type of enclosed space that does not have openings to permit the entrance of fresh air.

The ratio of inducer diameter to intake-duct diameter, which is 2:1 for the one in the test, could range from 1:1 to ratios larger than 2:1. Larger ratios might be needed in locations of low average wind velocities, and smaller ratios could be used in areas of high average wind velocities.

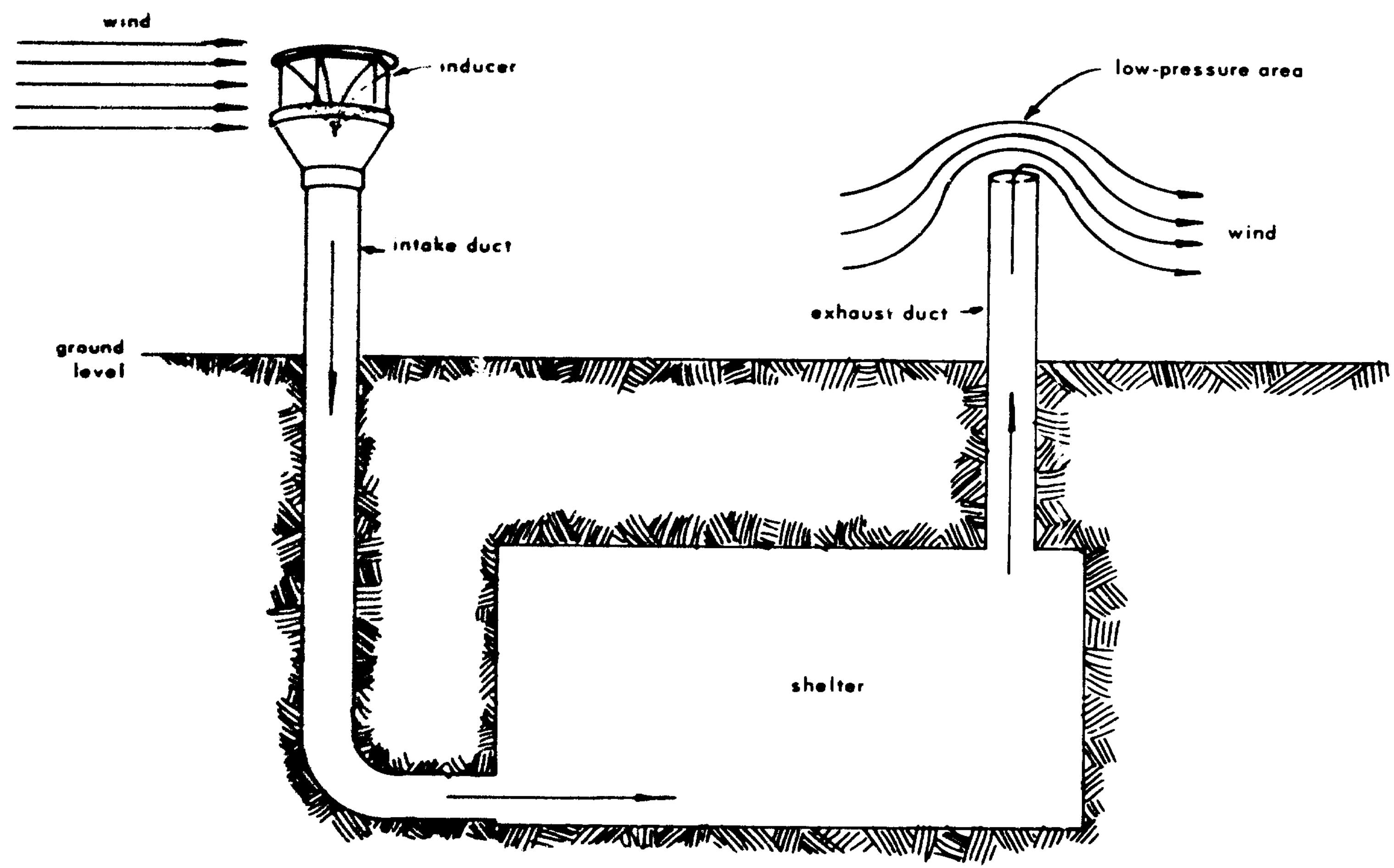

Figure 6. The use of wind for shelter ventilation.

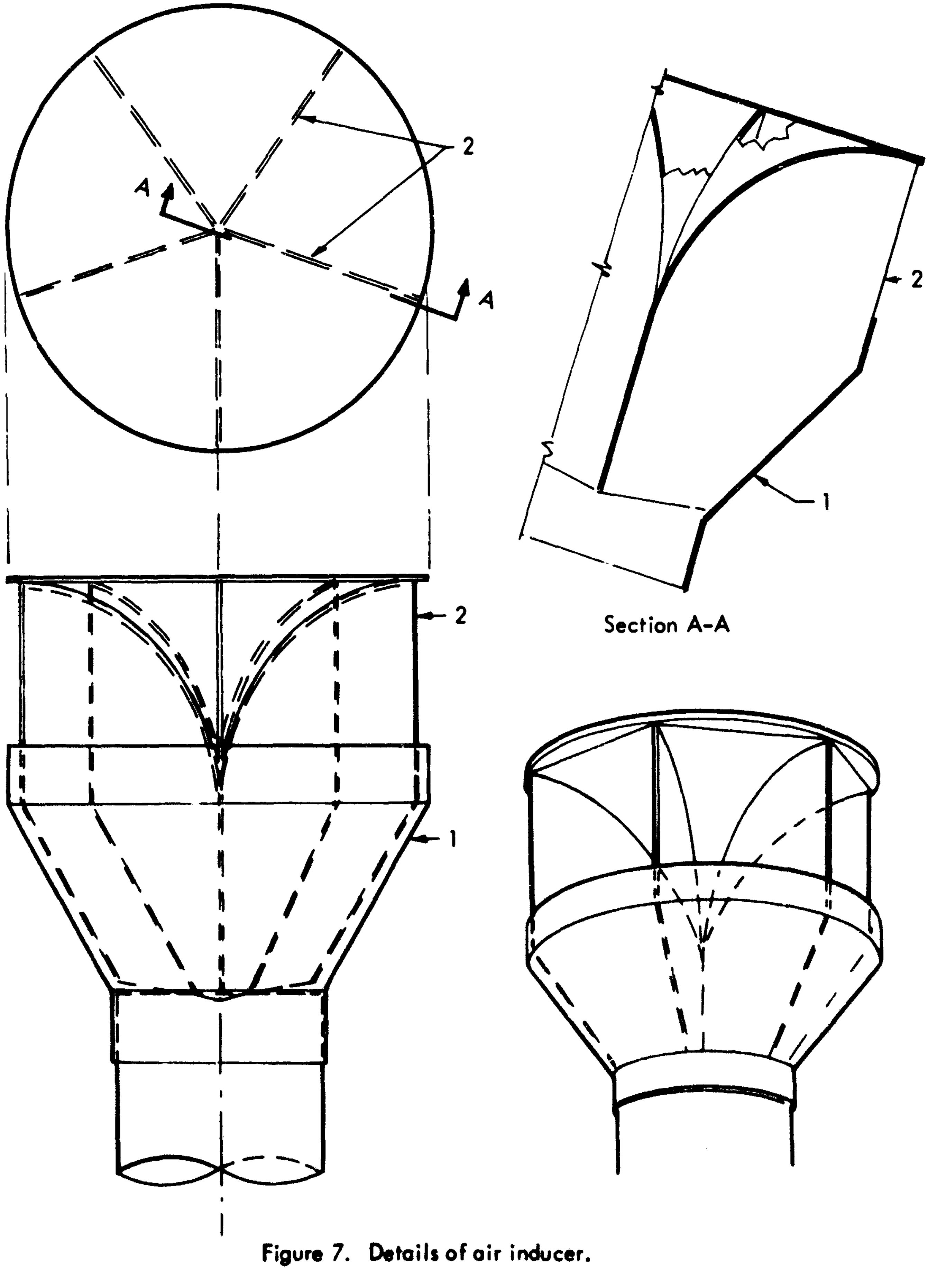

Figure 7. Details of air inducer.

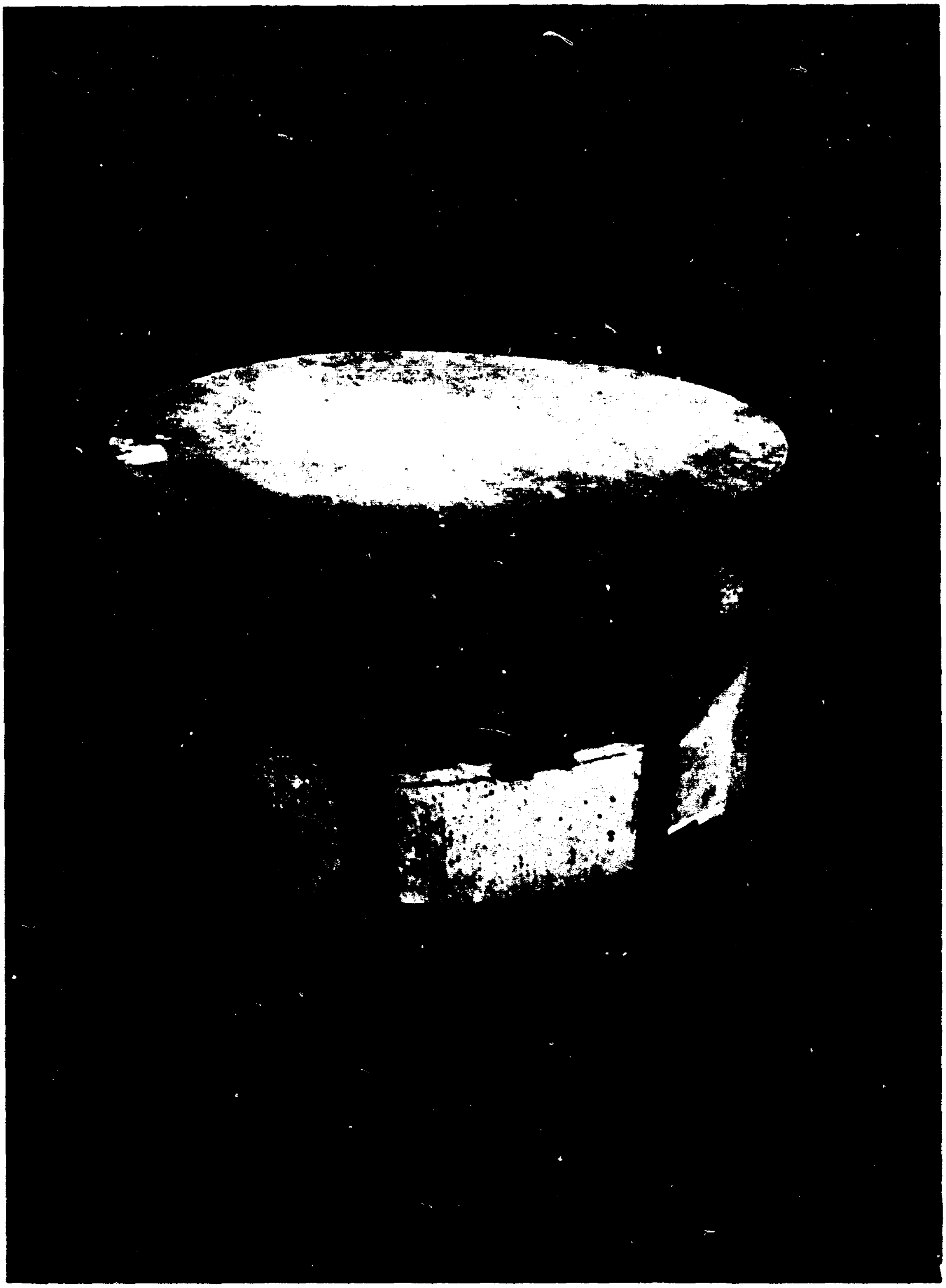

Figure 8. NCEL-designed air inducer.

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